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ELECTROMAGNETIC PROCESSES OCCURRING
IN ELECTRICAL CIRCUITS USED IN GEOPHYSICAL EXPLORATION

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/Figures are appended./

The problem of electromagnetic processes occurring in transmitting (feed) and receiving circuits arose in field studies in connection with the practical use of these circuits to establish an electric field in the earth. The importance of this problem becomes clear if the initial propositions and consequences resulting from the theory developed by A. N. Tikhonov /1, 2/, Corresponding Member, Academy of Sciences USSR, are taken into consideration.

The initial propositions are:

1. A solitary square-wave pulse is transmitted through a conductor grounded at both ends (transmitting dipole).

2. The wave front theoretically rises almost instantaneously, after which a constant current flows in the transmitting dipole.

Passing through the transmitting dipole into the earth, the square-wave pulse is transformed by the electrical properties of the rocks in the region under study and is influenced by the distance between the transmitting and receiving points. In particular, for the case of a homogeneous and isotropic earth, the time required for maximum current, or the establishment of the electric field in the earth, is expressed by the formula: t equals $0.314X^2/P$, where t is the characteristic time in seconds, X is the distance between the transmitting and receiving point in kilometers, and P is the resistivity of the earth in ohms per meter.

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For nonhomogeneous earth, the formula becomes somewhat more complex.

If we evaluate the full time necessary for maximum field at the receiving point for the lowest values of X (around 50 meters) used in practice, and for the customary values of resistivity P (of the order of 20 to 50 ohms per meter), we find a value of approximately 10^4 second. For the largest values of X (of the order of kilometers) used in practice, the time required for maximum field may be of the order of seconds. The form of the curve for field growth may be quite diverse.

Thus, we may now formulate the practical requirements for measuring circuits (transmitting and receiving dipoles) which are necessary for any method of conducting field studies.

1. Distortion of the square-wave pulse by the transmitting dipole (the conductor and the ground system) is permissible as long as the length of time necessary for maximum pulse to form at the ends of the dipole (at the grounds) is not greater than 10^{-5} second i.e., is more rapid by one order than the time for maximum field at the receiving point for the lowest values of X and P encountered in practical work.

2. Some distortion of the received pulse by the receiving dipole (conductor and grounding system) is permissible so long as it is not excessive.

As was pointed out above, the transmitting and receiving circuits are dipoles whose dimensions may vary with the distance between their centers, i.e., from several meters to several kilometers.

What are the processes that actually take place in the transmitting and receiving dipoles? Let us first consider the transmitting dipole.

The equivalent circuit of a transmitting dipole is shown in Figure 1, where AB is the length of the dipole conductor, CD is the return conductor (the ground in this case), R_1 is the effective resistance including the ground resistance and the internal resistance of the thyratron tube, R_2 is the resistance of the ground B (effective resistance), C is the capacitance between the conductor and ground, and L is the inductance of the conductor lying on the ground. The quantities C and L are distributed along the entire conductor length.

The square-wave pulse fed into the transmitting dipole is generated by a thyratron generator /3/ and rises to its maximum in approximately 10^{-7} second, the time for firing the thyratron.

Thus, the problem in this case reduces to the determination of the distortion of the form of the transmitted pulse due to reflected current and voltage waves which arise when the circuit is closed.

It is not difficult, however, to show that these oscillations do not last long enough to change materially the form of the square-wave pulse in the conductor.

Let us consider an average dipole, 100 meters long. If a conductor, one meter long, lying on the ground has an inductance of 10^{-6} henry and a capacitance of 15×10^{-12} farad, then for a dipole 100 meters long we have L equal to 10^{-4} henry and C equal to 15×10^{-10} farad. If we consider that the ohmic resistance of the conductor is very small and the

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leakage resistance very great, then the characteristic impedance of the conductor is $W = \sqrt{L_1/C_1} = \sqrt{10^{-6}H/15 \times 10^{-12}F} = 300$ ohms.

Since the ground resistance at the end of the conductor is of the order of 100 ohms, then the coefficient of reflection is equal to 100/300 equals 1/3.

A single wave is propagated in a conductor 100 meters long in $\sqrt{LC} = \sqrt{10^{-4}H \times 15 \times 10^{-10}F} = 4 \times 10^{-7}$ second. After quadruple reflection, the amplitude of the reflected wave in the conductor will only make up $(1/3)^4$ of the amplitude of the wave transmitted to the earth; i.e., about one percent and this occurs in $4 \times 4 \times 10^{-7}$ second equals 1.6×10^{-6} second.

Thus, a 100-meter dipole can lengthen the time necessary for the wave front of a square-wave pulse to reach its maximum only by 1.6×10^{-6} second, a magnitude fully admissible in practice.

If the length of the dipole is increased, say up to 100 meters, the wave front of the transmitted pulse may be lengthened by 1.6×10^{-5} second, which is fully satisfactory from the viewpoint of theoretical requirements, the more so, if we consider that a dipole 1,000 meters long corresponds to a distance between the transmitting and receiving points for which the time for establishing the field is measured in tenths of a second or even seconds.

The above propositions were checked experimentally in the following manner:

A single square-wave pulse was fed into a 200-meter dipole, grounded at both ends, by a thyratron generator (see circuit in Figure 2). The potential difference at the ground B was applied to the vertical plate of an oscilloscope. Closing of the circuit was regulated so that the horizontal sweep led the pulse of the thyratron generator by a certain time interval.

Figure 2 also shows a copy of one of the oscillograms obtained, which depicts the process of current growth in the transmitting dipole. The time dimension is placed beneath the oscillogram on the horizontal axis, which division of which equals 1×10^{-4} second (nonlinear scale).

From Figure 2 it is seen that, after a lapse of approximately 1×10^{-4} second after the beginning of the horizontal sweep, the potential difference from the ground B appears upon the vertical plates of the oscilloscope. A square-wave form for the current growth in the dipole is obtained, and even visual observation shows that the form of the square-wave pulse remains undistorted within a time interval of 1×10^{-5} second.

Let us now consider the receiving dipole.

The equivalent circuit for the receiving dipole is identical with the circuit for the transmitting dipole with the one difference that the resistance R_2, which is the leakage resistance of the grid of the input amplifier tube, is equal to 1/2 megohm /3/.

From the standpoint of wave processes, the phenomena occurring in this dipole must be similar to processes in the transmitting dipole, inasmuch as one end of the receiving dipole conductor is grounded through a low resistance R_1. Moreover, since it is not necessary to obtain minimum values of ground resistance in the receiving circuit, as it was in the transmitting circuit, then, as the experiment showed, the one-prong grounding installation has a resistance R_1 which approaches the characteristic impedance of

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the conductor, making conditions less favorable for the emergence of reflected waves in the conductor.

An experimental test confirmed the considerations presented above, as illustrated in Figure 3. Here an oscillogram depicts the passing of a square-wave pulse through the receiving dipole connected in the usual manner.

The oscillogram shows that the square-wave form of the pulse is not disturbed even within the narrow section of the curve corresponding to a time of 10^{-4} second.

Thus, we may consider it established that the electromagnetic processes which take place both in the transmitting and receiving circuits do not in practice distort the forms of the transmitted and received pulses.

The considerations and conclusions introduced above apply with equal strength to transmitting and receiving circuits used in direct-current electroprospecting. We use this fact for clarification of the following problem.

The so-called induction phenomenon is usually encountered in field electroprospecting. This is assumed to be due to the influence of the current in the transmitting conductor upon the receiving conductor and creates considerable noise during field measurements.

An oscillographic study of the processes in measuring circuits forces the conclusion that the induction phenomenon, to which reference is often made in the electroprospecting literature, does not exist. Actually, if we imagine that the electric field is established in the earth as fast as it is in the transmitting conductor, then the form of the pulse received would always be square and the measuring process for the given lines would be no different from the measuring process for short lines.

The impossibility of the emergence of inductive electromotive forces, in the receiving conductor was simply and cleverly proven by A. N. Tikhonov. His proof follows:

It is known that inductive electromotive forces are possibly only in a closed system having a definite area. If the system consists of two connected adjacent linear conductors, then inductive electromotive forces cannot arise.

An actual receiving circuit is a system consisting of two connected and adjacent conductors (the first conductor is the cable proper and the second conductor is the ground). In such a system, inductive electromotive forces cannot arise; in distinction to the usual system, however, the ground is not a linear conductor. As in nonlinear conductors, the inductive electromotive forces which are induced by the magnetic field of the transmitting cable's current when the transmitting circuit is closed arise in it.

However, since the electric field in the earth is dependent upon the characteristics of the electric layer, the pulse on the receiving electrodes may vary slightly from a square wave, i.e., may not be established instantaneously, for small distances between points and be considerably elongated in time for long distances between points. Inasmuch as measurements in the field are carried out by the compensation method under simultaneous closing of the transmitting and receiving circuits, while the curve for the compensating potential difference has a square-wave form in all

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cases, it becomes understandable why measurements of potential difference in the receiving circuit become more difficult with an increase in the distances between points.

On the basis of the above, the conditions used for measuring current strengths in the transmitting circuit by the accepted method must give correct results, while measurements of potential difference in the receiving circuit and, consequently, the values of resistivity calculated according to these measurements may be and actually are, as has now become clear, inconsistent with the actual values. As a consequence, the electrosounding curves obtained are distorted and their interpretation leads to incorrect conclusions concerning the geological structure of the region under study.

The accepted method of measuring potential difference as soon as the transmitting and receiving circuits are closed must be rejected. Instead, we suggest the following measuring methods for long lines, when the time required to set up the electric field in the earth becomes important.

1. Close only the transmitting circuit by an individual switch.

2. After a certain time lapse, necessary to establish the electric field in the earth, measure the potential difference by the usual method. The time, in seconds, necessary for full establishment of the field in the earth can be determined from the equation t plus X^2/P or t equals $1.5X^2/P$ where X is the length of AB in kilometers, and P is the resistivity of the earth in ohms per meter. It will be sufficient if the arithmetical average of previous measurements of P is used to determine this time. The first measurement should be made X^2/P seconds after the transmitting circuit is closed and the second control measurement, after $1.5X^2/P$ seconds.

After two or three soundings, the optimum times which must be used in the given region for measurements with various lengths of AB should be determined.

The power supply used in field conditions are sometimes not modern enough to maintain the current in the transmitting circuit at one level for several seconds or even tenths of seconds. Therefore, to avoid errors, the current which is actually flowing in the transmitting circuit during measurements of the potential differences must be taken into consideration in practice.

To decrease the flow of current, when it is necessary to keep the transmitting circuit closed for 5 to 10 seconds or more, a rheostat may be connected in series with it. After the circuit is closed, resistance may gradually be introduced between the time when the transmitting circuit is closed and the potential difference is measured.

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/Appended figures follow./

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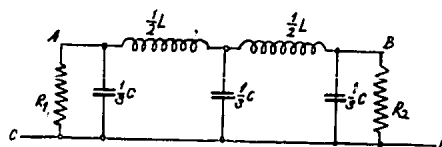
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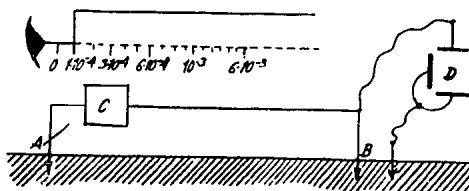Figure 1. Equivalent Circuit of a Transmitting Dipole

Figure 2. An Oscillogram, Showing Process of Current Growth in Trans-
mitting Dipole (above) and Circuit Connections for Transmit-
ting Dipole (below)
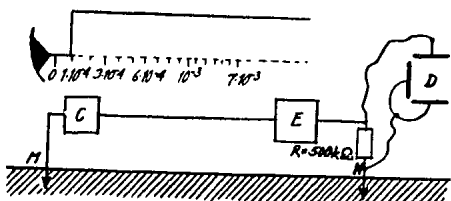A and B, dipole grounds; C, thyratron generator; D oscillo-
scope

Figure 3. An Oscillogram, Showing Process of Current Growth in Receiving
Dipole (above) and Circuit Connections for Receiving Dipole
(below)
M and N, dipole grounds; C, generator; D, oscilloscope; E,
filter

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